

# Higgs Decays in the Low Scale Type I See-Saw Model

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## Abstract

The couplings of the low scale type I See-Saw model are severely constrained by the requirement of reproducing the correct neutrino mass and mixing parameters, by the non-observation of lepton number and charged lepton flavour violating processes and by electroweak precision data. We show that all these constraints still allow for the possibility of an exotic Higgs decay channel into a light neutrino and a heavy neutrino with a sizable branching ratio. We also estimate the prospects to observe this decay at the LHC and discuss its complementarity to the indirect probes of the low scale type I see-saw model from experiments searching for the  $\mu \rightarrow e\gamma$  decay.

## 1 Introduction

It is well established experimentally on the basis of the neutrino oscillation data that neutrinos have non-zero masses which are much smaller than the charged lepton and quark masses, and that they mix. The enormous disparity between the magnitude of the neutrino masses and the masses of the charged leptons and quarks suggests that the neutrino masses are related to the existence of a new mass scale in physics, i.e., to new physics beyond the Standard Model (SM). The simplest extension of the SM, which allows to explain naturally the smallness of the neutrino masses and the existence of neutrino mixing, consists of introducing two right-handed (RH) fermions as  $SU(2)_L \times U(1)_Y$  singlets, usually known as RH neutrinos, which have Yukawa-type couplings with the SM Higgs and left-handed (LH) lepton doublets. Unless one imposes additional ad-hoc (global) symmetries, the RH neutrinos have also a Majorana mass term which breaks explicitly the total lepton charge conservation. In such type I see-saw scenarios [1], the light neutrinos are therefore predicted to be Majorana particles and their small masses are generated after the electroweak (EW) symmetry breaking due

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to the interplay between the neutrino Yukawa couplings and the Majorana masses of the RH neutrinos. The scale  $\Lambda$  at which the new physics manifests itself, which is set by the scale of masses of the RH neutrinos, can, in principle, have an arbitrary large value, up to the GUT scale of  $2 \times 10^{16}$  GeV and even beyond, up to the Planck mass. An interesting possibility, which can also be theoretically well motivated (see, e.g., [2, 3, 4]), is to have the new physics at the TeV scale, i.e.,  $\Lambda \sim (100 - 1000)$  GeV. Low scale see-saw scenarios usually predict a rich phenomenology at the TeV scale and are constrained by different sets of data, such as, e.g., the data on neutrino oscillations, from EW precision tests and on the lepton flavour violating (LFV) processes  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu^- - e^-$  conversion in nuclei. In the case of the TeV scale type I see-saw scenario of interest, the flavour structure of the couplings of the heavy Majorana neutrinos  $N_1$  and  $N_2$  to the charged leptons and the  $W^\pm$  bosons, and to the LH flavour neutrinos  $\nu_{\ell L}$  and the  $Z^0$  boson, are essentially determined by the requirement of reproducing the data on the neutrino oscillation parameters [5] (see also [6, 4]). The strongest constraints on the parameter space of this scenario is provided by the data on the  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow 3e$  decays and the  $\mu^- - e^-$  conversion in nuclei [7, 5, 8]. Given the constraints on the neutrino Yukawa couplings which follow from the current upper bound on the  $\mu \rightarrow e\gamma$  decay rate [9], the charged current (CC) and neutral current (NC) weak interaction couplings of the heavy Majorana neutrinos  $N_{1,2}$  are not sufficiently large to allow their direct production at the LHC with an observable rate [5].

In this Letter we consider the possibility of producing these new fermions from Higgs boson decays, in the scenario in which the see-saw mass scale is smaller than the Higgs boson mass.<sup>2</sup> Current collider searches exclude at the 95% C.L. Higgs masses below 114.4 GeV (LEP [11]) and the windows 127 GeV to 600 GeV (CMS [12]), 111.4 GeV to 116.6 GeV, 119.4 GeV to 122.1 GeV, and 129.2 GeV to 541 GeV (ATLAS [13]). We will concentrate here on the low mass allowed window and we will take as benchmark value a Higgs mass  $m_h = 125$  GeV, which is in agreement with the new particle recently discovered by the ATLAS and CMS experiments [14, 15], and which is at the moment a good candidate for a Standard Model Higgs boson. In this framework, the presence of a new Higgs boson decay channel, with heavy Majorana neutrinos in the final state, does not modify the SM Higgs boson production mechanisms at LHC, but enlarge the total Higgs decay width, thus lowering the decay branching ratios predicted in the Standard Model. We consider what are the constraints that one can impose on the size of neutrino Yukawa couplings in these scenarios from a possible observation of the new decay channel at LHC as well as the interplay with the limits obtained using the data from the experiments on LFV processes involving the charged leptons.

The text is organized as follows: in section 2 we recapitulate the formalism and discuss the relevant parameter space in type I see-saw scenarios with RH neutrino masses at the electroweak scale. In section 3 we discuss the new Higgs decay channel and in section 4 we analyze quantitatively the prospects for production and detection of the heavy RH neutrinos in Higgs decays at the LHC. All the relevant results are summarized in the last section of the paper.

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<sup>2</sup> A similar study has been done recently in [10] in the context of inverse see-saw models with heavy singlet fermions at the EW scale. However, in the analysis performed in [10] the relevant constraints on the see-saw parameter space and the limits on the Yukawa couplings, which arise from neutrino oscillation data and the experimental searches of charged lepton flavour violation, were not included.

## 2 Preliminary Remarks

The light neutrino Majorana mass matrix is generated from the following Lagrangian, arising in type I see-saw extensions of the SM:

$$\mathcal{L}_\nu = -\overline{\nu_{\ell L}}(M_D)_{\ell a}^* \nu_{aR} - \frac{1}{2} \overline{\nu_{aL}^C} (M_N)_{ab}^* \nu_{bR} + \text{h.c.}, \quad (1)$$

where  $\nu_{aL}^C \equiv C \overline{\nu_{aR}}^T$ ,  $C$  being the charge conjugation matrix,  $M_N = (M_N)^T$  is the  $k \times k$  Majorana mass matrix of the right-handed (RH) neutrinos  $\nu_{aR}$ , and  $M_D$  is a  $3 \times k$  neutrino Dirac mass matrix which is generated by the matrix of neutrino Yukawa couplings after the electroweak (EW) symmetry breaking. In the following we consider the TeV scale type I see-saw scenarios with two RH neutrinos discussed in [7, 5, 8].<sup>3</sup>

Taking into account eq. (1), and working in the basis in which the RH neutrino mass matrix is diagonal, the couplings of the heavy Majorana neutrino mass eigenstates  $N_1$  and  $N_2$  with the SM leptons and the SM Higgs boson  $h$  are given by:

$$\mathcal{L}_H^N = -\frac{gM_k}{4M_W} \overline{\nu_{\ell L}} (RV)_{\ell k} (1 + \gamma_5) N_k h + \text{h.c.} \quad (2)$$

where  $R \simeq (M_D M_N^{-1})^*$  and  $V$  is the unitary matrix that diagonalises the RH neutrino mass matrix,  $M_N \simeq V^* \text{diag}(M_1, M_2) V^\dagger$ , with  $M_{1,2} > 0$ . The combination  $(RV)$  parametrises the mixing between the SM active left-handed (LH) flavour neutrinos  $\nu_{\ell L}$  and the SM singlet RH neutrinos  $\nu_{aR}$  and determines the charged current and the neutral current weak interaction couplings of the heavy Majorana neutrinos  $N_k$  to the  $W^\pm$  and  $Z^0$  bosons:

$$\mathcal{L}_{CC}^N = -\frac{g}{2\sqrt{2}} \bar{\ell} \gamma_\alpha (RV)_{\ell k} (1 - \gamma_5) N_k W^\alpha + \text{h.c.}, \quad (3)$$

$$\mathcal{L}_{NC}^N = -\frac{g}{4c_w} \overline{\nu_{\ell L}} \gamma_\alpha (RV)_{\ell k} (1 - \gamma_5) N_k Z^\alpha + \text{h.c.}, \quad (4)$$

The elements of the matrix  $(RV)$  should satisfy the following constraint which is characteristic of the type I see-saw mechanism under discussion

$$\left| \sum_k (RV)_{\ell' k}^* M_k (RV)_{k \ell}^\dagger \right| \simeq |(m_\nu)_{\ell' \ell}| \lesssim 1 \text{ eV}, \quad \ell', \ell = e, \mu, \tau. \quad (5)$$

Here  $m_\nu$  is the Majorana mass matrix of the LH flavour neutrinos generated by the see-saw mechanism. The upper limit  $|(m_\nu)_{\ell' \ell}| \lesssim 1 \text{ eV}$ ,  $\ell, \ell' = e, \mu, \tau$ , follows from the existing data on the neutrino masses and on the neutrino mixing [19]. For the values of the masses  $M_k$  of the heavy Majorana neutrinos  $N_k$  of interest for the present study,  $M_k \lesssim 125 \text{ GeV}$ , the simplest scheme in which the constraint (5) can be satisfied is [5] that in which the two heavy Majorana neutrinos  $N_1$  and  $N_2$  form a pseudo-Dirac neutrino  $N_{PD}$  [20, 21]:  $M_2 = M_1(1+z)$ , where  $z \ll 1$ , and  $N_{PD} = (N_1 \pm i N_2)/\sqrt{2}$ . In the scenario where the CC and NC couplings of  $N_{1,2}$  are “sizable” leading to observable effects at low energies, the requirement of reproducing the correct neutrino oscillation parameters determines the couplings  $(RV)_{\ell 1}$  and  $(RV)_{\ell 2}$  in

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<sup>3</sup>Type I see-saw scenarios with two heavy Majorana neutrinos having masses by few to several orders of magnitude below the GUT scale of  $\sim 2 \times 10^{16} \text{ GeV}$  have been discussed, e.g., in [16, 17, 18].

eqs. (3) and (4). The concrete expressions depend on whether the neutrino masses exhibit a normal hierarchy (NH) or an inverted hierarchy (IH) and read [5]:

$$|(RV)_{\ell 1}|^2 = \frac{1}{2} \frac{y^2 v^2}{M_1^2} \frac{m_3}{m_2 + m_3} \left| U_{\ell 3} + i \sqrt{m_2/m_3} U_{\ell 2} \right|^2, \quad \text{NH}, \quad (6)$$

$$|(RV)_{\ell 1}|^2 = \frac{1}{2} \frac{y^2 v^2}{M_1^2} \frac{m_2}{m_1 + m_2} \left| U_{\ell 2} + i \sqrt{m_1/m_2} U_{\ell 1} \right|^2 \simeq \frac{1}{4} \frac{y^2 v^2}{M_1^2} |U_{\ell 2} + i U_{\ell 1}|^2, \quad \text{IH}, \quad (7)$$

$$(RV)_{\ell 2} = \pm i (RV)_{\ell 1} \sqrt{\frac{M_1}{M_2}}, \quad \ell = e, \mu, \tau, \quad (8)$$

where  $v \simeq 174$  GeV and in eq. (7) we have used the fact that for the IH spectrum one has  $m_1 \simeq m_2$ . The parameter  $y$  in the expressions above represents the largest eigenvalue of the matrix of neutrino Yukawa couplings  $m_D/v$  [5]:

$$y^2 v^2 = 2 M_1^2 (|(RV)_{e1}|^2 + |(RV)_{\mu 1}|^2 + |(RV)_{\tau 1}|^2). \quad (9)$$

For  $M_{1,2} \lesssim 125$  GeV, the most stringent upper limits on  $|(RV)_{e1}^* (RV)_{\mu 1}|$ , and thus on the magnitude of  $y$ , can be obtained from the existing experimental upper bound on the rate of the lepton flavour violating (LFV) process  $\mu \rightarrow e \gamma$  [5, 8]. Taking the best fit values of the neutrino oscillation parameters [22], we get the upper limits:

$$y \lesssim 0.042 \quad \text{for NH with } M_1 = 100 \text{ GeV}, \quad (10)$$

$$y \lesssim 0.056 \quad \text{for IH with } M_1 = 100 \text{ GeV}. \quad (11)$$

These upper limits are roughly of the same order as the bottom Yukawa coupling,  $y_b = m_b/v \simeq 0.024$ . It is then interesting to explore the impact of the heavy neutrinos with a possibly sizable Yukawa coupling in the Higgs phenomenology. In this Letter we will discuss the possibility of observing the exotic Higgs decays  $h \rightarrow \nu_{\ell L} + \overline{N_{PD}}, \overline{\nu_{\ell L}} + N_{PD}$  at the LHC. For brevity we will denote these decays generically as  $h \rightarrow \nu N$  in what follows.

### 3 New Higgs Decay Channels

The decay rate of the Higgs boson to a SM fermion-antifermion pair is given by, at leading order in QCD corrections,

$$\Gamma(h \rightarrow f \bar{f}) = \frac{1}{16\pi} \left( \frac{m_f^2}{v^2} \right) m_h \left( 1 - \frac{4 m_f^2}{m_h^2} \right)^{3/2} N_c(f), \quad (12)$$

with the usual color factor  $N_c(f)$  equal to 1 and 3 in the case of final state leptons and quarks, respectively. For a light Higgs particle,  $m_h < 160$  GeV, the dominant decay channel is  $h \rightarrow b \bar{b}$ , which involves the Yukawa coupling  $y_b = m_b/v \simeq 0.024$ .

In the type I see-saw scenario of interest, the Higgs boson can also decay into a light and a heavy pseudo-Dirac neutrino  $N_{PD}$  provided  $M_1 < m_h$ . In this case, the Higgs decay rate is directly related to the neutrino Yukawa coupling  $y$  defined in eq. (9). Indeed, from the Lagrangian eq. (2) and eq. (9) we obtain:

$$\begin{aligned} \Gamma(h \rightarrow \nu N) &\equiv \sum_{\ell=e,\mu,\tau} (\Gamma(h \rightarrow \nu_{\ell L} \overline{N_{PD}}) + \Gamma(h \rightarrow \overline{\nu_{\ell L}} N_{PD})) \\ &= \frac{1}{16\pi} y^2 m_h \left( 1 - \frac{M_1^2}{m_h^2} \right)^2, \end{aligned}$$

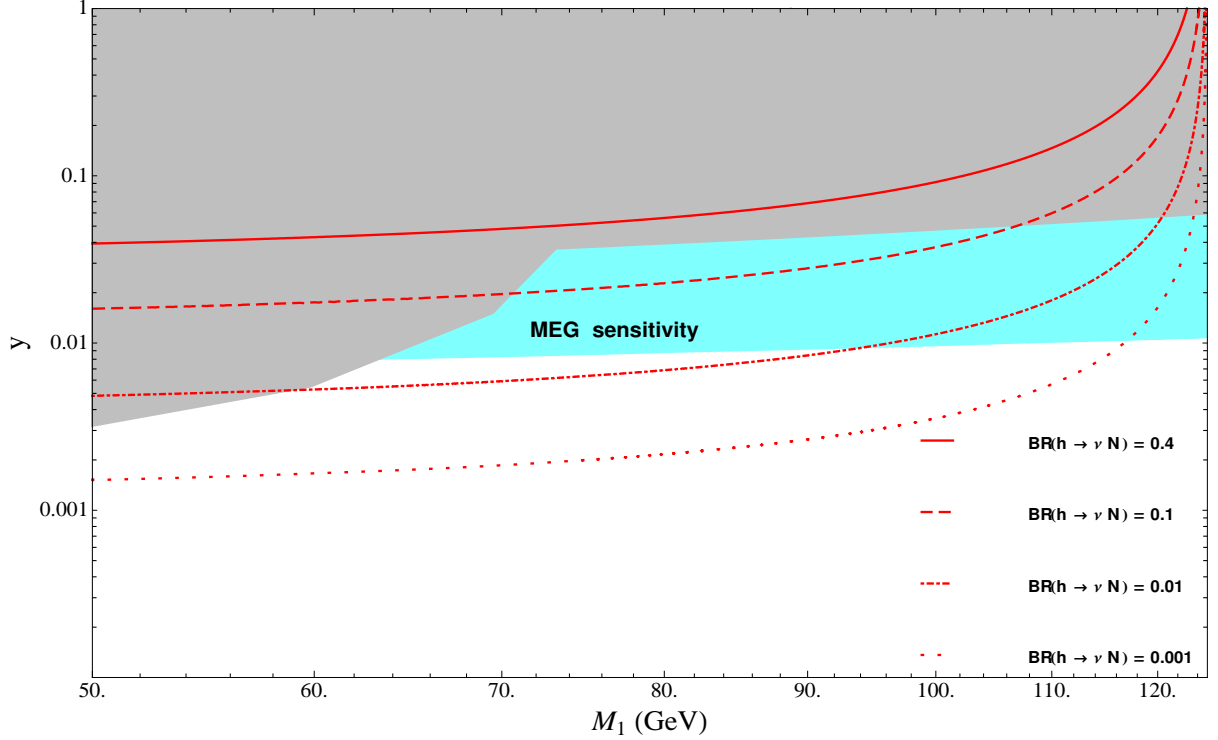


Figure 1: Values of the neutrino Yukawa coupling  $y$  probed by Higgs decays into  $N_{PD}$  for  $m_h = 125$  GeV (solid lines). The gray region is excluded by LEP2 data [24] and searches of lepton flavour violation [9, 23]. The cyan area represents the region of the parameter space which can be probed by the MEG experiment with the projected sensitivity to  $\text{BR}(\mu \rightarrow e\gamma) = 10^{-13}$ .

Taking as benchmark values  $m_h = 125$  GeV and  $M_1 = 100$  GeV, we obtain that  $\Gamma(h \rightarrow \nu N)/\Gamma(h \rightarrow b\bar{b}) \simeq 0.19 (y/0.05)^2$ . Hence, the decay channel  $h \rightarrow \nu N$  could have a sizable branching ratio if the upper limit on the Yukawa coupling  $y$ , obtained using the MEG upper bound on the  $\mu \rightarrow e\gamma$  decay rate and quoted in eq. (11), is saturated. Conversely, the search for the Higgs decay  $h \rightarrow \nu N$  can provide limits on the parameters of the low scale see-saw model which are competitive to those from the searches for the  $\mu \rightarrow e\gamma$  decay, when  $m_h > M_1$ . On the other hand, in the case  $M_1 > m_h$  the exotic Higgs decay channels are,  $h \rightarrow \nu N \rightarrow \nu\nu Z$ ,  $\nu\ell W$  which have a rate suppressed by the fourth power of  $y$  as well as by the three-body decay phase space. In view of the present upper limit on  $y$  obtained from the existing experimental upper bounds on the rates of the lepton flavour violation processes  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow 3e$  and  $\mu - e$  conversion in nuclei [5, 8], we conclude that the decay rates in these channels are too small to produce any observable effect. Hence, we will concentrate in what follows just on the possibility  $M_1 < m_h$ .

We show in Fig. 1 the values of  $y$  as function of the see-saw scale  $M_1$  corresponding to different values of  $\text{BR}(h \rightarrow \nu N)$ , for a fixed value of the Higgs boson mass,  $m_h = 125$  GeV. We also show the excluded region (gray area) by the results of i) the search for the  $\mu \rightarrow e\gamma$  decay with the MEG experiment [9], ii) the search for  $\mu - e$  conversion in Ti [23] and iii) the search for heavy singlet neutrinos in  $Z$  boson decays at LEP2 [24]. It follows

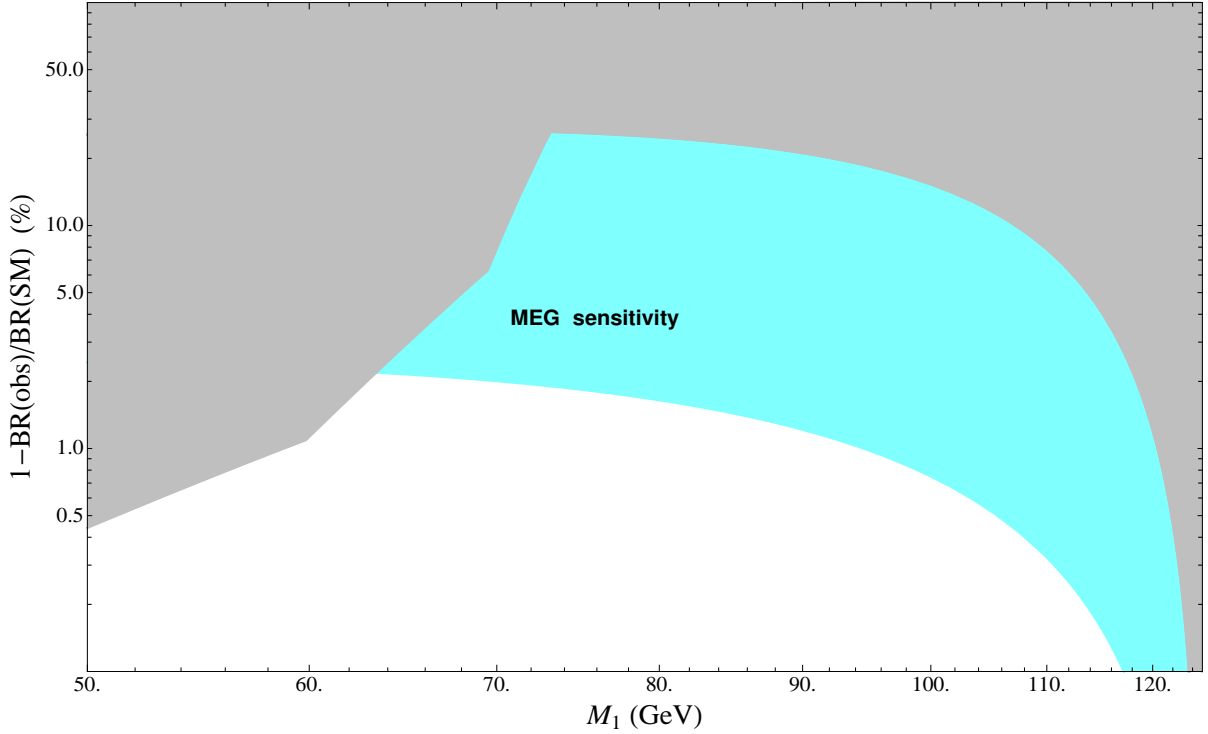


Figure 2: Relative reduction of the Standard Model Higgs boson branching fraction to a generic channel for  $m_h = 125$  GeV. The color convention is the same as in Fig. 1.

from the plot that the present limits on the low scale see-saw mechanism do not preclude the possibility of a Higgs boson decaying into a heavy and a light neutrino with a branching ratio which can be as large as 20%, which, as we will see in the next section, can be observed at the LHC. Alternatively, the search for the exotic Higgs decay  $h \rightarrow \nu N$  could provide the strongest limits on the parameter space of the low scale see-saw mechanism for RH masses smaller than the Higgs mass. We also show in the plot as a cyan area the projected sensitivity reach of the MEG experiment searching for the  $\mu \rightarrow e\gamma$  decay with a branching ratio  $\text{BR}(\mu \rightarrow e\gamma) \gtrsim 10^{-13}$ , which may allow to exclude  $\text{BR}(h \rightarrow \nu N) \gtrsim 1\%$  for  $M_1 \gtrsim 100$  GeV.

Furthermore, opening a new decay channel also modifies the branching ratios of the Higgs decay to a generic channel  $X$  with respect to the corresponding SM prediction ( $\text{BR}(\text{SM})$ ):

$$\text{BR}(h \rightarrow \nu N) \equiv \frac{\Gamma(h \rightarrow \nu N)}{\Gamma(h \rightarrow \nu N) + \Gamma_{\text{tot}}^{\text{SM}}} = 1 - \frac{\text{BR}(\text{obs})}{\text{BR}(\text{SM})} \quad , \quad (13)$$

$\Gamma_{\text{tot}}^{\text{SM}}$  being the total decay width of the Higgs boson in the Standard Model [25]. We show in Fig. 2 the maximal relative change of the branching fraction into a generic SM final state which arises in the low scale see-saw model, which is allowed by the current bound on the rate of the  $\mu \rightarrow e\gamma$  decay. It follows from the plot that deviations as large as 25% are possible in this model.<sup>4</sup> We also show in the plot the maximal relative change allowed if the MEG experiment reaches the sensitivity  $\text{BR}(\mu \rightarrow e\gamma) \sim 10^{-13}$  without finding a positive

<sup>4</sup> Notice that in this class of see-saw scenarios, in the case of IH light neutrino mass spectrum, a strong

signal. Conversely, the detection of a positive signal of  $\mu \rightarrow e\gamma$  decay at MEG would imply the possibility of deviations from the SM branching ratios larger than 2%, up to 25%, for  $70 \text{ GeV} \lesssim M_1 \lesssim 100 \text{ GeV}$ .

## 4 Searches for the New Channel $h \rightarrow \nu N$ at LHC

We have simulated with Madgraph [26] the process of production of a Higgs boson at the LHC, which decays  $h \rightarrow \nu N$ . We consider explicitly the final state with the heavy neutrino subsequently decaying into a charged lepton and an on-shell  $W$  boson, which in turn decays producing two jets.<sup>5</sup> The processes of interest in our analysis are then:

$$pp \rightarrow h \rightarrow \nu_{\alpha L} \ell_{\beta}^{+} jj, \bar{\nu}_{\alpha L} \ell_{\beta}^{-} jj, \quad \alpha, \beta = e, \mu, \tau. \quad (14)$$

The branching fractions corresponding to the decays into the charged lepton  $\ell_{\alpha}$  can be obtained from equations (6) and (7), the result being:

$$\text{BR}(N_{PD} \rightarrow W \ell_{\alpha}) = \frac{m_3}{m_2 + m_3} \left| U_{\alpha 3} + i \sqrt{m_2/m_3} U_{\alpha 2} \right|^2 \sum_{\beta} \text{BR}(N_{PD} \rightarrow W \ell_{\beta}) \quad \text{for NH}, \quad (15)$$

$$\text{BR}(N_{PD} \rightarrow W \ell_{\alpha}) = \frac{m_2}{m_1 + m_2} \left| U_{\alpha 2} + i \sqrt{m_1/m_2} U_{\alpha 1} \right|^2 \sum_{\beta} \text{BR}(N_{PD} \rightarrow W \ell_{\beta}) \quad \text{for IH}. \quad (16)$$

In these equations (see, e.g., [27]),

$$\begin{aligned} \sum_{\alpha} \text{BR}(N_{PD} \rightarrow W \ell_{\alpha}) &= \frac{(1 - \mu_W)^2 (1 + 2\mu_W)}{(1 - \mu_W)^2 (1 + 2\mu_W) + (1 - \mu_Z)^2 (1 + 2\mu_Z)}, & \text{if } \mu_Z < 1, \\ \sum_{\alpha} \text{BR}(N_{PD} \rightarrow W \ell_{\alpha}) &= 1, & \text{if } \mu_Z > 1, \end{aligned} \quad (17)$$

where  $\mu_W = (\frac{m_W}{M_1})^2$  and  $\mu_Z = (\frac{m_Z}{M_1})^2$ .

In our analysis we will only consider final states involving  $e$  and  $\mu$  due to the lesser efficiency in identifying  $\tau$  leptons. Then, the total branching fraction of the process of interest is:

$$\begin{aligned} \text{BR}_{\text{Total}} &= \text{BR}(h \rightarrow e^{-} \bar{\nu} jj) + \text{BR}(h \rightarrow \mu^{-} \bar{\nu} jj) + \text{BR}(h \rightarrow e^{+} \nu jj) + \text{BR}(h \rightarrow \mu^{+} \nu jj) \\ &= \text{BR}(h \rightarrow \nu N) [ \text{BR}(N \rightarrow W e) + \text{BR}(N \rightarrow W \mu) ] \text{BR}(W \rightarrow jj), \end{aligned} \quad (18)$$

which can be calculated from eqs. (13), (15), (16) and (17), with  $\text{BR}(W \rightarrow jj) = 0.676$  [28]. To estimate the relative branching ratio of the decay of the heavy neutrinos into  $e + \mu$  flavours, we show in Fig. 3 the upper limit on the coupling  $y$  for different values of the

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suppression of  $\mu - e$  transitions might be possible for particular values of the CP violating phases in the neutrino mixing matrix if  $0.15 \lesssim \sin \theta_{13} \lesssim 0.2$  [8]. In this case, the best upper limit on the neutrino Yukawa coupling follows from the EW precision data:  $y \lesssim 0.06 M_1 / (100 \text{ GeV})$  [5]. This bound corresponds to  $\text{BR}(h \rightarrow \nu N) \lesssim 34\%$  for  $M_1 \gtrsim 72 \text{ GeV}$ .

<sup>5</sup> The authors in [10] considered, within an inverse see-saw scenario, the alternative possibility to detect a heavy pseudo-Dirac singlet fermion through the fully leptonic decay mode:  $h \rightarrow \bar{\nu}_{\alpha L} N_{PD} + \text{h.c.} \rightarrow \bar{\nu}_{\alpha L} \nu_{\beta L} \ell_{\gamma} \ell_{\delta} + \text{h.c.}$



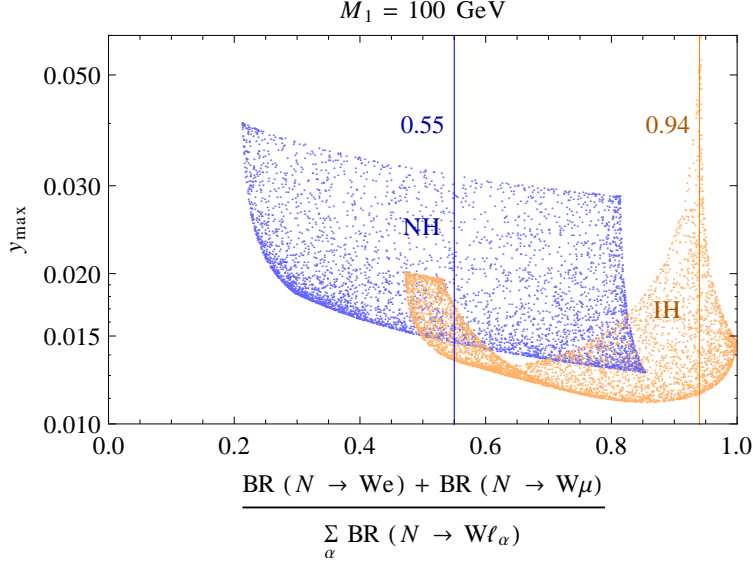


Figure 3: Upper limit on the Yukawa coupling for various values of the relative branching fraction for decays into  $e$  and  $\mu$  for normal hierarchy (blue) and for inverted hierarchy (orange) and  $M_1 = 100$  GeV. We also show in the plot the benchmark points taken in our analysis.

relative branching ratio, calculated using eqs. (15) and (16) by taking the best fit values of the neutrino oscillation parameters [22] and varying the Dirac and Majorana phases of the neutrino mixing matrix between 0 and  $2\pi$ . We find that for the values of the Yukawa coupling that saturate the limits in eqs. (10) and (11), the relative branching ratio into  $e + \mu$  is approximately equal to 0.94 for the IH and is in the range 0.20 – 0.80 for NH. We will then use for our analysis the values  $(\text{BR}(N \rightarrow W e) + \text{BR}(N \rightarrow W \mu)) / \sum_{\alpha} \text{BR}(N \rightarrow W \ell_{\alpha}) = 0.55$  and 0.94 for NH and IH, respectively.

Now we define the signal identification and the corresponding reconstruction algorithm. Since our channel is one charged lepton, two jets plus missing energy, and following the detector coverage for the LHC experiments, we apply the following basic kinematical acceptance on the transverse momentum  $p_T$ , rapidity  $\eta$  and the particle separation  $\Delta R$ :

$$\begin{aligned} p_T(\ell) &> 10 \text{ GeV}, \quad |\eta_{\ell}| < 2.5, \\ p_T(j) &> 15 \text{ GeV}, \quad |\eta_j| < 2.5, \\ \Delta R(jj) &> 0.4, \quad \Delta R(j\ell) > 0.4, \end{aligned} \tag{19}$$

where the particle separation is defined as  $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ ,  $\Delta\phi$  and  $\Delta\eta$  being the azimuthal angular separation and the rapidity difference between two particles. To further simulate the detector effects, we assume that the lepton and jet energies are smeared with a Gaussian distribution according to

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b, \tag{20}$$

where  $a_{\ell} = 5\%$  and  $b_{\ell} = 0.55\%$  for leptons, while  $a_j = 100\%$  and  $b_j = 5\%$  for jets [29].



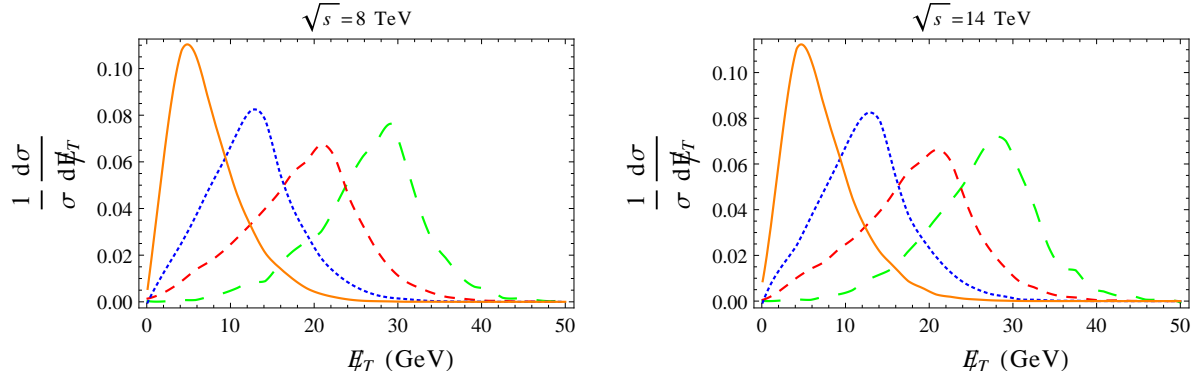


Figure 4: Reconstructed normalized distributions  $\frac{1}{\sigma} \frac{d\sigma}{dE_T}$  vs. the missing transverse energy,  $E_T$ , for various RH neutrino masses:  $M_1 = 120 \text{ GeV}$  (continuous line),  $M_1 = 110 \text{ GeV}$  (dotted line),  $M_1 = 100 \text{ GeV}$  (short dashed line) and  $M_1 = 90 \text{ GeV}$  (long dashed line).

In order to construct efficient cuts to further reduce the background we have simulated the signal for  $M_1 = 90 \text{ GeV}$ ,  $100 \text{ GeV}$ ,  $110 \text{ GeV}$  and  $120 \text{ GeV}$  using center of mass energies of  $8 \text{ TeV}$  and  $14 \text{ TeV}$ . We show the corresponding normalized differential cross sections, after including the smearing, for the missing transverse energy  $E_T$  (Fig. 4), for the total invariant mass  $m_{jj\ell}$  (Fig. 5), which is peaked at the heavy neutrino mass, for the invariant mass of the jets  $m_{jj}$  (Fig. 6), which is peaked at the  $W$  boson mass, and for the reconstructed transverse mass  $m_T$  (Fig. 7), which has a Jacobian peak at the Higgs boson mass. From these distributions, it follows that the following cut on the missing transverse energy

$$E_T > 10 \text{ GeV}, \quad (21)$$

and on the reconstructed masses

$$\begin{aligned} 80 \text{ GeV} < m_{jj\ell} < 130 \text{ GeV}, \\ m_W - 10 \text{ GeV} < m_{jj} < m_W + 10 \text{ GeV}, \\ 110 \text{ GeV} < m_T < 130 \text{ GeV}. \end{aligned} \quad (22)$$

will not reduce significantly the signal for a wide range of RH neutrino masses.

There are Standard Model backgrounds that lead to similar final states to our signal events, the most important being quark-gluon collisions when the final quark emits an off-shell  $W$  boson which subsequently decays leptonically. Using Madgraph we have calculated the cross sections for the background processes. Here we ignore the faked leptons from heavy quarks like  $b$  or  $c$ , assuming that our stringent separation requirement for the charged leptons will effectively remove them.

For the sake of illustration, we list in table 1 the total cross sections for the background processes as well as for the signal (with masses  $M_1$  of  $90 \text{ GeV}$ ,  $100 \text{ GeV}$  and  $110 \text{ GeV}$  and  $y = 0.04$ ), after basic cuts, eq. (19), missing transverse energy cut, eq. (21), and mass cuts, eq. (22), for  $8 \text{ TeV}$  and  $14 \text{ TeV}$ . The reconstruction procedure outlined above effectively selects out the signal kinematics and substantially suppresses the SM backgrounds.

We conservatively calculate the statistical significance to observe a signal by

$$S = \frac{N_s}{\sqrt{N_s + N_b}}, \quad (23)$$

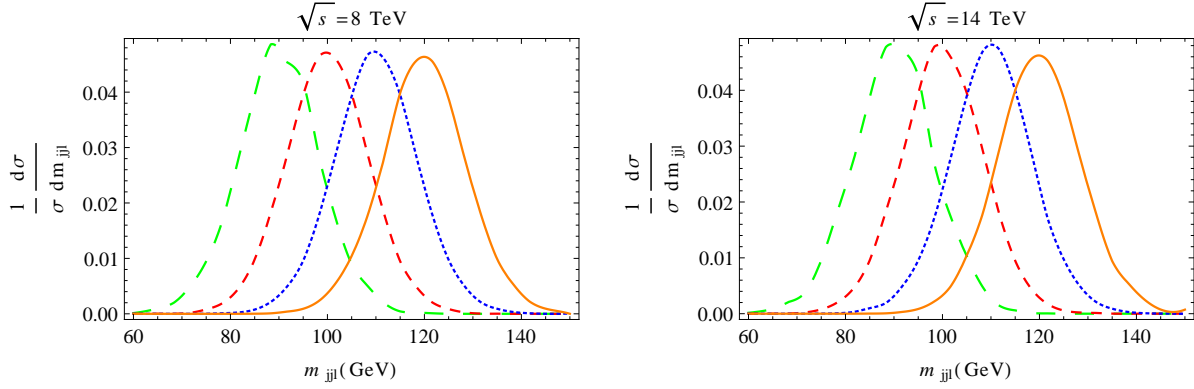


Figure 5: Reconstructed normalized distributions  $\frac{1}{\sigma} \frac{d\sigma}{dm_{jjl}}$  vs. the total invariant mass  $m_{jjl}$ . See Fig. 4 for details.

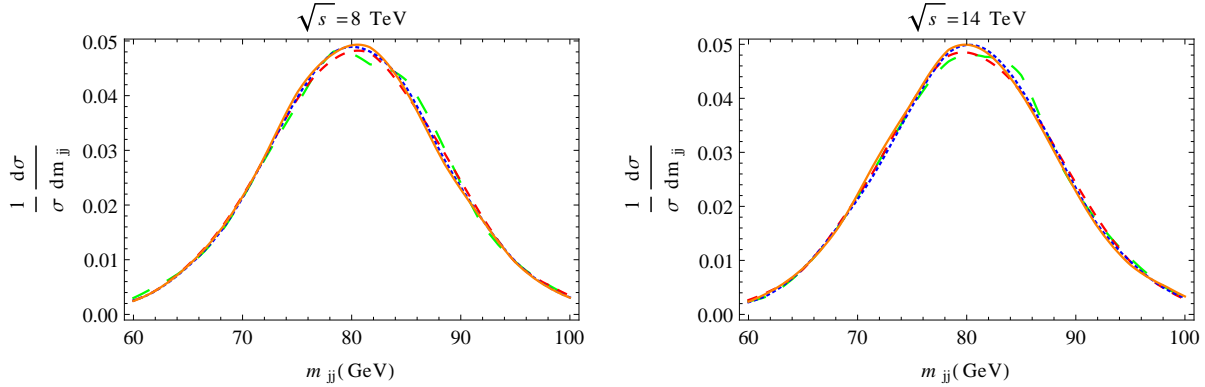


Figure 6: Reconstructed normalized distributions  $\frac{1}{\sigma} \frac{d\sigma}{dm_{jj}}$  vs. the invariant mass of the jets  $m_{jj}$ . See Fig. 4 for details.

where  $N$  corresponds to the number of events, and the subscripts  $s$  and  $b$  refer to the signal and the background respectively. Using the algorithm described above, we have estimated the values of the neutrino Yukawa coupling  $y$  that yield statistical significances of  $3\sigma$  and  $5\sigma$  for luminosities of  $1 \text{ fb}^{-1}$  and  $10 \text{ fb}^{-1}$  and center of mass energies of 8 TeV and 14 TeV. The results are shown in Fig. 8.

It follows from Fig. 8 that the best sensitivity to the neutrino Yukawa coupling can be reached for a light neutrino mass spectrum with inverted hierarchy. This is due to the fact that in this case  $\text{BR}(N \rightarrow We) + \text{BR}(N \rightarrow W\mu)$  can be, as shown in Fig. 3, plausibly close to one. In particular, values of  $y$  as small as 0.02 can be probed at LHC with a luminosity of  $10 \text{ fb}^{-1}$ . Such values of the neutrino Yukawa coupling can be directly tested by the MEG experiment [9] searching for the  $\mu \rightarrow e\gamma$  decay (see Fig. 1). We find then an interesting interplay between collider searches of RH neutrinos through Higgs decays and LFV observables, which may be relevant for excluding type I see-saw scenarios with RH neutrino masses at the electroweak scale.

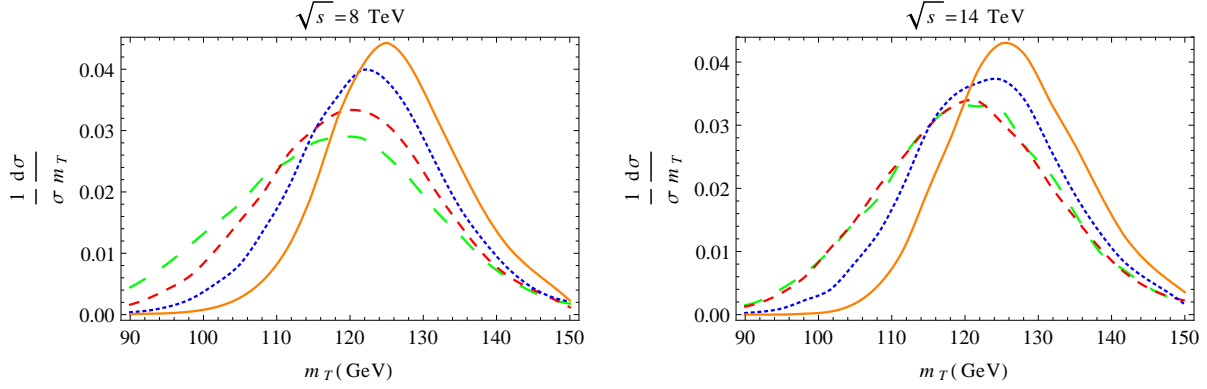


Figure 7: Reconstructed normalized distributions  $\frac{1}{\sigma} \frac{d\sigma}{dm_T}$  vs. the transverse mass  $m_T$ . See Fig. 4 for details.

$\sigma(pb)$				
$\sqrt{s}$	Process	Basic Cuts Eq. (19) NH (IH)	$\cancel{E}_T$ Cut Eq. (21) NH (IH)	Mass cuts Eq. (22) NH (IH)
8 TeV	Signal, $M_1 = 90$ GeV	0.061 (0.105)	0.060 (0.103)	0.033 (0.056)
	Signal, $M_1 = 100$ GeV	0.132 (0.225)	0.117 (0.200)	0.067 (0.114)
	Signal, $M_1 = 110$ GeV	0.051 (0.087)	0.035 (0.059)	0.019 (0.032)
	Background	1235	1189	3.45
14TeV	Signal, $M_1 = 90$ GeV	0.155 (0.265)	0.154 (0.263)	0.083 (0.142)
	Signal, $M_1 = 100$ GeV	0.339 (0.579)	0.299 (0.511)	0.171 (0.293)
	Signal, $M_1 = 110$ GeV	0.130 (0.222)	0.088 (0.151)	0.048 (0.082)
	Background	2635	2537	7.40

Table 1: Effects of the kinematical cuts on the production cross section at the LHC for the signal  $pp \rightarrow h \rightarrow jj\ell^+\nu + \text{h.c.}$  and the corresponding SM background assuming normal (inverted) hierarchy. We set the neutrino Yukawa coupling:  $y = 0.04$ .

## 5 Conclusions

In this Letter we discussed quantitatively the possibility of producing and detecting at LHC the heavy  $SU(2)_L \times U(1)_Y$  singlet fermions which appear in the context of TeV scale type I see-saw extension of the Standard Model with a mass  $M$  at the electroweak scale. The recent discovery of a new scalar particle at LHC, which up to now exhibits properties that are consistent with those of the SM Higgs boson, opens the possibility of testing such kind of see-saw scenarios in collider experiments through the observation of new exotic Higgs decay channels in which the heavy fermions are produced.

The minimal version of the TeV scale type I see-saw scenario of interest contains two heavy Majorana neutrinos  $N_{1,2}$  with masses  $M_{1,2}$ . The requirement of reproducing the data on the neutrino masses and mixing determines the flavour structure of the neutrino Yukawa couplings as well as of the charged current and the neutral current weak interaction couplings of  $N_{1,2}$  to the  $W^\pm$  and  $Z^0$  bosons in the model. The existing low energy phenomenological constraints on the indicated scenario can be satisfied if the two heavy Majorana neutrinos

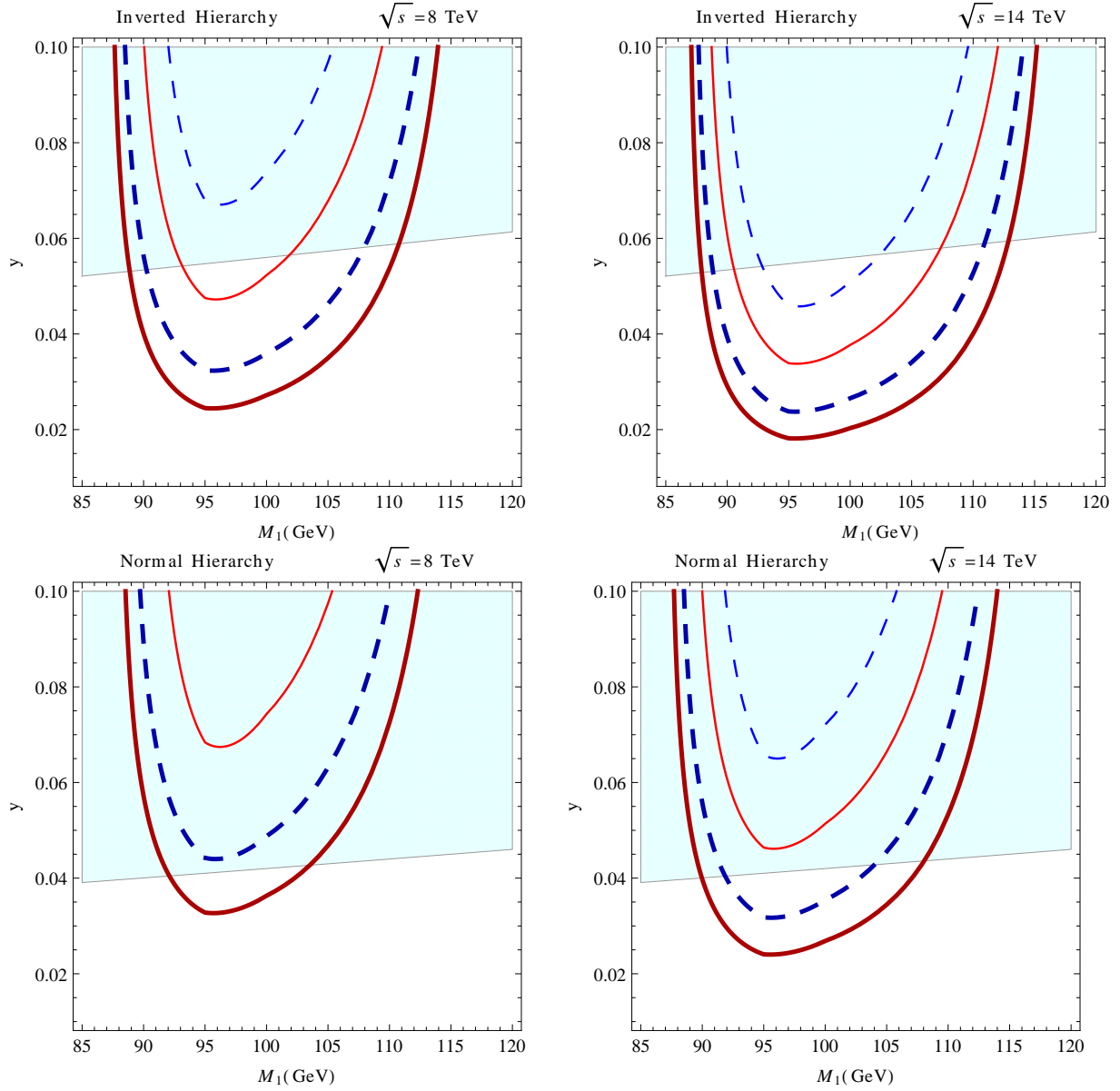


Figure 8: Sensitivity of the LHC to the coupling  $y$  vs  $M_1$  at  $3\sigma$  (continuous line) and  $5\sigma$  (dashed line) and an integrated luminosity  $\mathcal{L} = 1 \text{ fb}^{-1}$  (thin line) and  $\mathcal{L} = 10 \text{ fb}^{-1}$  (thick line), for inverted hierarchy (upper panels) and normal hierarchy (lower panels) and for  $\sqrt{s} = 8 \text{ TeV}$  (left panels) and  $\sqrt{s} = 14 \text{ TeV}$  (right panels). The shaded region is excluded by the current experimental upper limit  $\text{BR}(\mu \rightarrow e\gamma) \leq 2.4 \times 10^{-12}$  [9].

form a pseudo-Dirac particle,  $N = (N_1 + iN_2)/\sqrt{2} \equiv N$ , with  $M_2 = M_1(1 + z)$ ,  $z \ll 1$ . As was shown in [5], the type I see-saw scenario of interest is characterised by four real parameters: the mass  $M_1 \equiv M$ , which sets the see-saw scale, the mass splitting parameter  $z \ll 1$ , a neutrino Yukawa coupling  $y$  and a CP violation phase. Only two of these parameters - the mass  $M$  and the Yukawa coupling  $y$ , are relevant for the study performed in the present article.<sup>6</sup>

<sup>6</sup>The mass splitting  $z$ , for instance, is too small to have observable effects at LHC.

In this Letter we analyzed the prospects of revealing the existence of the additional SM singlet heavy Majorana neutrinos  $N_{1,2}$ , forming a pseudo-Dirac fermion  $N_{PD} \equiv N$ , in the case in which the Higgs particle is heavier than  $N_{1,2}$  and decays with one charged lepton and two jets in the final state via the chain:  $h \rightarrow \nu N \rightarrow \nu \ell W \rightarrow \nu \ell jj$ , where both  $N$  and  $W^\pm$  are on mass shell. The results of our numerical analysis are reported in Table 1, where it is shown that, after imposing the relevant cuts on the total number of events, the QCD background can be drastically reduced allowing the signal to be visible if enough luminosity can be accumulated at the LHC. The strength of the latter is strictly related to the values of the neutrino Yukawa coupling  $y$  and the see-saw scale  $M$ .

We find that if  $y \gtrsim 0.02$  and  $90 \text{ GeV} \lesssim M \lesssim 110 \text{ GeV}$ , then the heavy RH neutrinos (in the form of the pseudo-Dirac particle  $N$ ) can be observed at LHC with a statistical significance in the range of 3 to 5  $\sigma$  for a luminosity of  $10 \text{ fb}^{-1}$  and a center of mass energy of 14 TeV (Fig. 8). With a more sophisticated search strategy even smaller Yukawa couplings could be probed at the LHC.

Sizable neutrino Yukawa couplings in the type I see-saw scenario considered can also be probed by experiments searching for charge lepton flavour violation (LFV), such as the MEG experiment which is devoted to the search for the  $\mu \rightarrow e\gamma$  decay. If the MEG experiment eventually observes the  $\mu \rightarrow e\gamma$  decay with a branching ratio  $\text{BR}(\mu \rightarrow e\gamma) > 10^{-13}$ , the low scale type I see-saw scenario can be directly tested at LHC through  $h \rightarrow \nu N$  decays. Conversely, if no positive signal is detected in the MEG experiment and the upper limit  $\text{BR}(\mu \rightarrow e\gamma) < 10^{-13}$  is obtained, this will lead to a more stringent limit on the neutrino Yukawa coupling  $y$  that will exclude the possibility of producing and detecting the new heavy pseudo-Dirac neutrino  $N$ .

As the results obtained in the present Letter show, the study of the properties of the Higgs boson observed at LHC will have important implications for the understanding of the origins of the neutrino masses and mixing as well.

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